Date: 06/28/2020

EIC Detector R&D Progress Report

Project ID: eRD24
Project Name: A Proposal for Silicon Detectors with high Position and Timing Resolution as Roman Pots at EIC
Period Reported: from 01/2020 **to** 06/2020
Project Leader:
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Abstract

Roman Pots are an integral part of the detector system of an EIC and essential for the success of its physics program. Roman Pots will provide a critical contribution to the study of exclusive production processes in ep collisions, i.e. deeply virtual Compton scattering as well as tagging protons from deuteron breakup in eA interactions, among others. This proposal aims at setting the performance requirements for a Roman Pot detector at EIC, focusing on spatial granularity, timing resolution and acceptance. In addition, an innovative silicon-based technology, called Low Gain Avalanche Diode (LGAD), will be studied as it has the potential to combine in a single sensor fine spatial resolution and precise timing. More specifically, the AC-coupled version of LGADs (AC-LGADs) will be studied and prototypes fabricated at BNL to establish spatial and timing performance as well as the minimal possible inactive area that is critical for placing such sensors as close as possible to the beam. The performance of AC-LGADs will be compared to alternative sensors too. Given the need of fast-timing at EIC and the growing interests in LGAD technology to meet those needs, the scope of this proposal is expanded to include the study for the application of such technology in other detector designs for EIC, i.e. a pre-shower calorimeter. Additionally, we intend to collaborate with colleagues who have proposed such technologies for tracking and TOF. In response to recommendations from the committee, we have expanded the scope of the proposal and strengthened the team of co-investigators to include the development of an architecture for the readout electronics and experts in readout electronics and ASIC design.

Past

What was planned for this period?

In the past year the plan was to finalize the design for a set of AC-LGADs and to begin wafer fabrication of AC-LGADs at the BNL silicon fabrication facility in the Instrumentation Division. We also planned to study electrical and timing performance of alternative silicon sensor types, i.e. 3D sensors, used in pixel detectors at the LHC and HL-LHC, that have high radiation tolerance properties, and compare their performance to one of the AC-LGADs produced at BNL.

What was achieved?

Before discussing the progress on the AC-LGAD development, it is useful to contextualize the requirements for these sensors found from full Geant4 simulations. In the previous R&D period, these detailed simulations were carried out to demonstrate the detector requirements for a successful physics program using Roman Pots. As a reminder, Table 1 summarizes the transverse momentum smearing from various contributions.

	Ang Div. (HD)	Ang Div. (HA)	tx Smear	50μm pxl	500 μm pxl	1.3mm pxl
δp_T[MeV/c] - 275 GeV	40	28	20	6	11	26
δp_T[MeV/c] - 100 GeV	22	11	9	9	11	16
δp_T[MeV/c] - 41 GeV	14	-	10	9	10	12

Table 1: Summary of p_T-smearing contributions from beam angular divergence (high divergence, HD, and high acceptance, HA configurations), crab cavity rotation induced vertex smearing, and various detector pixel size choices.

From this table, as presented previously, the angular divergence contribution is generally the largest contribution to the smearing, but only in the case where the "high divergence" (maximal luminosity) beam configuration is used. In the high acceptance configuration, the impact of the angular divergence on the overall smearing is reduced, and is now comparable to the contribution from the crab cavity rotation of the bunch. Because of this, the removal of the smearing contribution from the crab cavity rotation is of the highest priority. In order to remove this contribution, **fast timing is required (~30 - 40 ps),** as detailed in the previous report. Without the fast timing, this contribution would increase the overall smearing in the high acceptance configuration by nearly a factor of $\sqrt{2}$, but would be even worse at lower-p_T where the overall smearing has the largest effect.

The high acceptance configuration serves the purpose of improving low-p_T acceptance by decreasing the beta functions at the Roman Pots, allowing the detectors to be moved closer to the beam (i.e. decreasing the 10σ distance). Since the physics program relies heavily on the measurement at low-p_T in order to determine the normalization of the impact parameter distribution, this running mode will be the one driving the requirements. That being said, all optimizations of detector requirements should be done using the high acceptance beam configuration numbers, further enforcing the need for the removal of the vertex smearing due to crab cavity rotation via fast timing.

From this same study, we determined that the detector pixels need to be at least as small as 500 x 500 μm2 in order to not have a comparable smearing contribution to the other effects at 275 GeV. Currently available LGAD sensors for the HL-LHC have 1.3 x 1.3 mm2 pixels, which would provide smearing contributions outside of our specifications as shown in Table 1. The 500 x 500 um2 pixelation could be achieved with reasonable effort on the readout electronics, while anything smaller would be a significant effort and increased cost, especially in the readout electronics. We therefore conclude that a **500 x 500 um2 pixel meets our physics needs, while also keeping costs reasonable**.

Given the basic requirements on the sensors driven by Geant4 simulations, we will now discuss the progress on the sensor development. The process flow for the fabrication of AC-LGAD in a clean room is mature. We completed the design of a photolithographic mask set to be used in the next batch of AC-LGAD fabrication (

Figure 1). Masks have already been purchased. The wafer layout features larger devices, and of different sizes (from 2 x 2 mm2 to 1.4 x 1.4 cm2). For the design, we leveraged the knowledge matured in previous LGAD and AC-LGAD batches. The metal layer of the new batch, only, (which defines the AC-coupled electrodes) is still to be designed as it is the last photolithographic step (to be performed after a couple of months from the starting of the fabrication in a clean room). A logical next step we plan to take in the next period is to quantify the yield in larger structures. We inserted devices to continue the testing of the slim edges in an effort to limit the dead area at the border of the AC-LGAD. From previous results we saw that a very limited number of tight-spaced guard rings is sufficient to hold the high bias voltage. In particular, the devices may be tested for trench termination (an activity started in the previous semester), to further limit the extension of the dead area (Figure 2). An extension of the lateral dead area of 100 mm is already within reach.

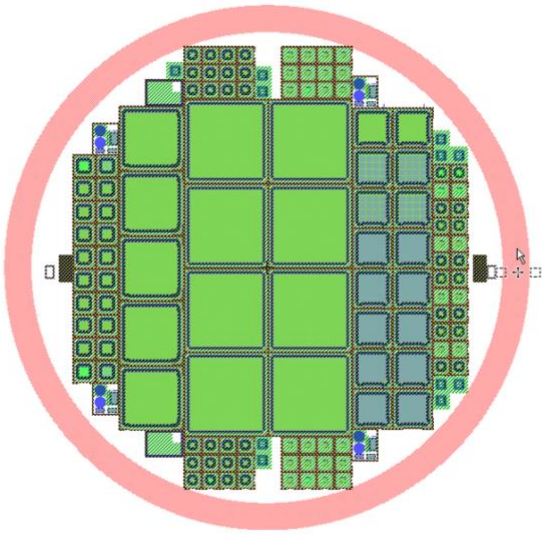

Figure 1: Layout of the 4” wafer, populated with AC-LGAD devices of different sizes.

In the meantime, in a few AC-LGAD wafers that were under fabrication, we replaced the old metal with a new metal featuring non-standard shapes. In particular, we designed *zigzag* strips and patterned the top metal accordingly (Figure 3). The purpose of zigzag geometry is to achieve a finer position resolution with a limited number of read-out channels, exploiting the signal spreading that naturally takes place in an AC-LGAD sensor, similarly to the case of a gas detector. Electrical I-V characterization at the probe station shows functional devices. After the I-V testing, we deposited the passivation (anti-scratch layer) which now needs to be opened in the wire-bonding pads (activity temporarily suspended due to the COVID 19 situation).

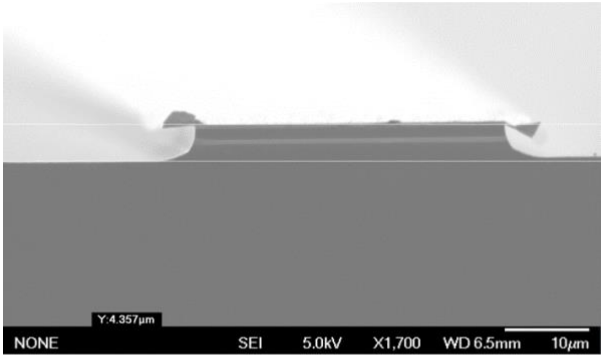

Figure 2: Trench etched into silicon, as an option for AC-LGAD termination

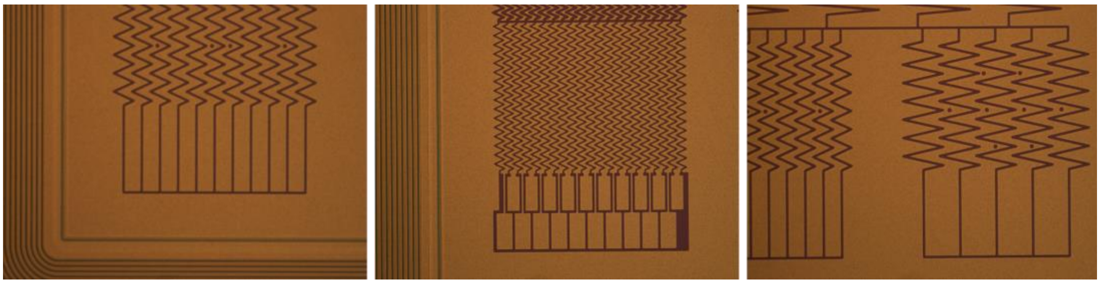

Figure 3: Layout of zigzag metal strips, included in the latest batch of AC-LGAD at BNL.

While these zigzag devices have not been tested in a test beam yet, we were able to test an AC-LGAD strip sensor in the 120 GeV proton test beam at FNAL (https://arxiv.org/abs/2006.01999), see Figure 4. The measurements confirm the expected AC-LGAD properties, such as 100% fill factor, fine position resolution smaller than the strip pitch of 100 μm (in this study, limited to 50 μm by the spatial resolution of the telescope in the set-up used), timing resolution compatible with LGADs of same gain and read-out by the same electronics. Such properties had already been inferred with standard laboratory tests, such as Transient Current Techniques analysis and radioactive source tests carried out at BNL and by international collaborators (https://iopscience.iop.org/article/10.1088/1748-0221/14/09/P09004; https://doi.org/10.1016/j.nima.2020.163479) .

Prior to test beams, in our lab we performed TCT (Transient Current Technique) scans (see Figure 5) and tests with radioactive sources (^{90}Sr, simulating MIPs) (Figure 6) on a few devices cut from each fabricated wafers, to assess the AC-LGAD performance as a function of different process parameters (e.g. dielectric thickness, gain layer dose, n+ dose). Actions to mitigate the effect of the low-resistance path seen in Figure 5 (a) and (b), which creates spurious conductive paths over the whole active area when the laser or a MIP strikes at the border, will be implemented in the next batch. The TCT scans consist in a laser beam scanning the active area of the sensor, and injecting charge into the device, while one (or multiple) sensor channels are readout.

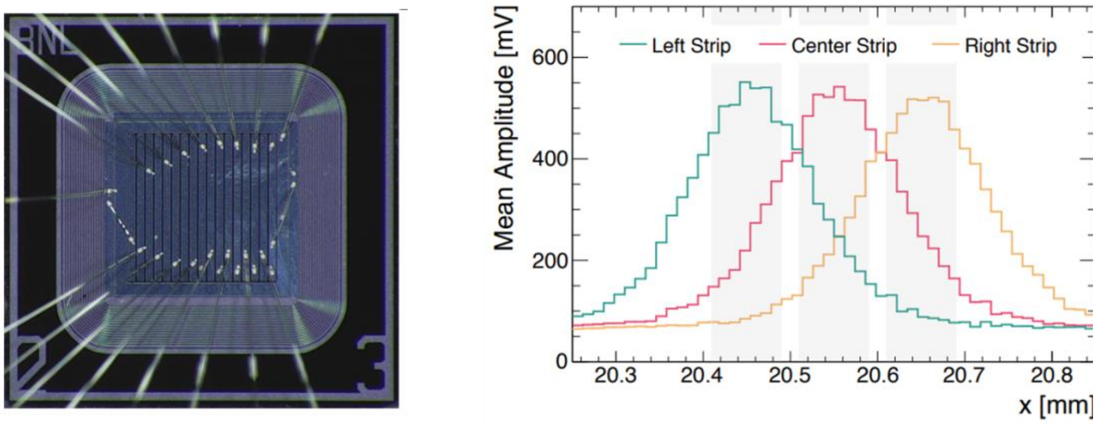

Figure 4: Test Beam at FermiLab: AC-LGAD consisting of 16 AC-coupled metal strips at 100 μm pitch (left), and the mean amplitude in three contiguous strips as a function of the reconstructed hit position (right).

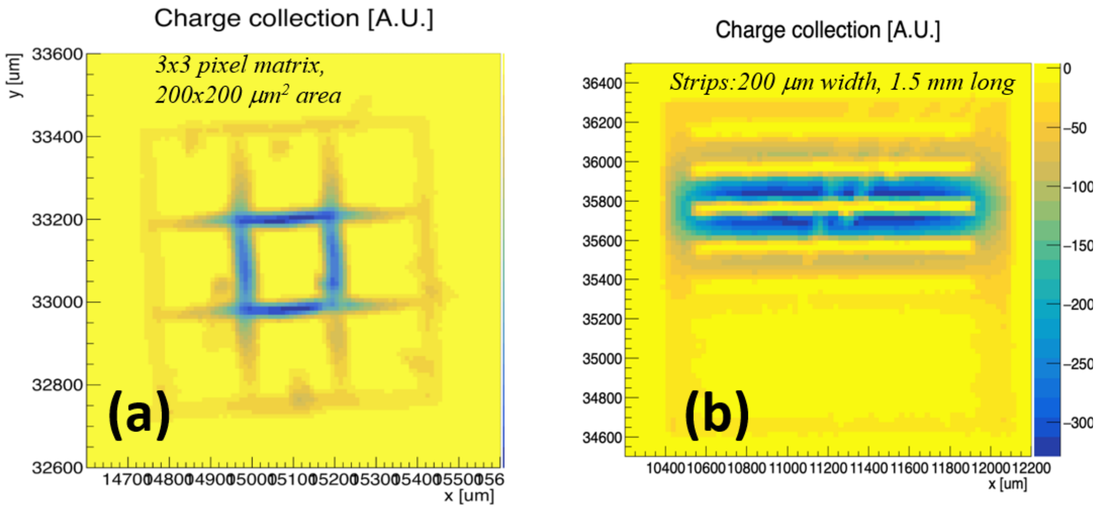

Figure 5: Dynamic measurements routinely performed on AC-LGAD devices: (a) TCT scan of a 3x3 AC-LGAD pixel matrix, (b) TCT scan of a AC-LGAD strip sensor. The collected charge (in arbitrary units) in one channel is shown as a function of the x-y position of the IR laser position on the sensor surface.

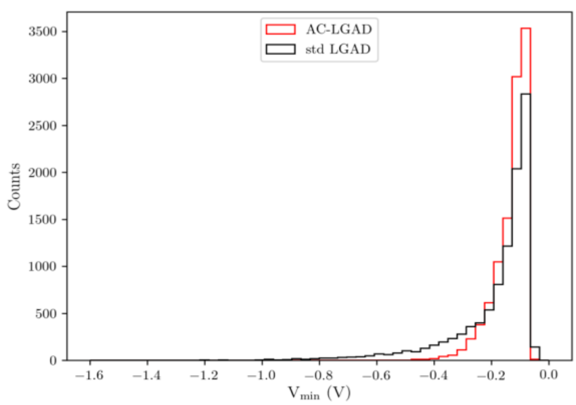

Figure 6: Dynamic measurements routinely performed on AC-LGAD devices: pulse height spectrum of an AC-LGAD vs an LGAD of the same gain detecting MIPs from ^{90}Sr. This type of measurement is used to assess the gain of the (AC-)LGADs.

While we could not test the timing performance of 3D detectors in the lab due to laboratory closure as a consequence of the COVID-19 pandemic, we prefer LGAD technology over 3D due to the higher capacitance (x5) of the latter devices. Specifically, one of the main challenges for the project is the development of the readout chip. A fast readout implies a high power consumption in the front end amplifier (as the current is drawn by the first transistor), and higher capacitances imply a proportionally higher current and power consumption. Notice that studies evaluating the timing of 3D detectors consider extremely small devices (made by just a few columns and, as such, having very small active areas, for example: https://indico.cern.ch/event/918298/contributions/3880603/attachments/2049821/3435837/3d_bfr_aft_irrad._36th_RD50_2.pdf). The 3D sensors are used in pixel detectors at HL-LHC, very close to the IR due to their radiation tolerance, and although they do not exhibit the co-called "Landau" noise (which ultimately sets the upper limit on the timing resolution in LGADs), their use as timing detectors is not foreseen due to their high capacitance.

Expanding the scope: application for a preshower detector

Photon and π_0 meson measurements is the primary goal of the electromagnetic calorimetry in particle physics experiments. The opening angle between two photons from a high momentum π_0 meson decay decreases as $1/p_{\pi 0}$, and at high enough π_0 momentum $p_{\pi 0}$ two photons appear in the EMCal in a close proximity to each other, so that the EMCal response to a pair of decay photons becomes indistinguishable from the response to a single photon with the energy equal to a sum of decay photon energies. Preshower detectors with granularity higher than that of the EMCal serve to extend the π_0/γ discrimination to higher momenta, as well as to improve photon position measurements and e/h separation.

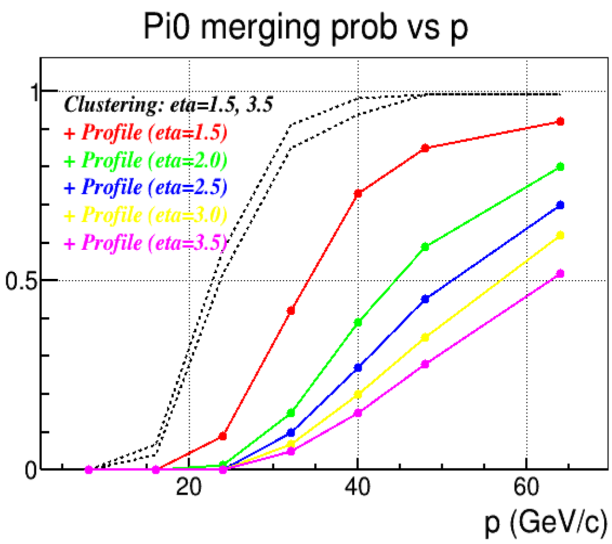

Figure 7: Probability for two decay photons to merge (to be indistinguishable from a single photon) as a function of π_0 momentum for an endcup W/SciFi EMCal with a tower size of 2.5x2.5 cm^2 located at 3m from the collision point, with towers oriented parallel to the beam line (non-projective geometry); black dotted lines - after clustering (two photons are reconstructed if two distinct local maxima are seen in the EMCal); coloured lines - in addition to clustering, shower profile analysis is applied to merged clusters; shown for different pseudorapidity bins.

A number of EIC physics topics rely on high momentum p0 measurements in Semi-Inclusive and Exclusive DIS processes. In hadron endcap the particle momenta extend to 100 GeV/c and beyond (for a proton beam energy of 275 GeV). For rapidity h>1, the EMCal is planned to be positioned at ~3m along the beam line from the collision point. A high granularity EMCal (with tower transverse size ~2.5cm) can provide a clean separation of two decay photons only up to p0 momentum of ~20 GeV/c (when two distinct local maxima are seen in the EMCal). Precise analysis of the shower profile of merged clusters can extend such a capability to ~40 GeV/c. However, this performance deteriorates for a non-orthogonal impact (e.g. for the EMCal with non-projective geometry), due to a wider shower profile and its larger fluctuations in the EMCal transverse plane. These are summarized in Figure 7. EMCal with projective geometry would mitigate such an issue. However such a large area endcap EMCal, with diameter of ~5m, with tower orientation (and possibly shape and size) varying for different (r,f), to fit within a very space restricted area, is viewed as a significant challenge.

A Preshower detector located just in front of the EMCal based on Silicon with granularity of a few mm or finer will considerably extend the momentum range for π_0/γ discrimination. Selecting the converter width of $2X_0$ would allow the majority of the photons to convert in order to be detected in the Si sensors, with a negligible impact on the EMCal resolutions. The shower particles at the exit of the converter are distributed typically within ~1mm around the photon axis. The minimal separation between two photons from a 100 GeV/c π_0 decay at 3m from the interaction vertex is ~8mm. Therefore even coarsely segmented sensors can easily distinguish two decay photons, if they both start showering in the converter.

Future studies will include optimization for a converter width, and for a number of layers, to compromise between the efficiency for a photon (or both photons from a π_0 decay) to be detected in Si sensors and the impact on the EMCal resolutions.

What was not achieved, why not, and what will be done to correct?

The studies that were planned for this period were successfully completed. However, detailed studies will continue in the next period to converge on the determination of the physics performance requirements, on the detector layout and on the charge sharing properties of AC-LGADs. For the latter the upcoming new wafer production will be important, as these properties will depend on the pixel size, pitch as well as other parameters, for example the doping of the resistive layer. Charge collection measurements of the silicon 3D sensors have been so far unsuccessful due to the large capacitance of 3D sensors, greater than the specifications of the system set-up available at BNL, and the interruption of laboratory activities caused by the COVID-19 pandemic. However, the plan to study 3D detectors have a low priority, given the concerns on their application in this project.

How did the COVID-19 pandemic and related closing of labs and facilities affect progress of your project?

We had to suspend the fabrication of AC-LGAD with zigzag pads, cancel a test-beam at FNAL that would have characterized such geometries, and delay the starting of the new AC-LGAD batch production. Tests on slim edges have also been suspended, as well as additional laboratory testing of AC-LGADs structures. However, data-analysis of previously collected data has continued, for example the study and publication of AC-LGAD strip sensor performance with the 120 GeV proton beam at FNAL [https://arxiv.org/abs/2006.01999]

How much of your FY20 funding could not be spent due to pandemic related closing of facilities?

We expect most of the requested funds will be spent by the end of FY20 with the exception of travels ($5k)

Do you have running costs that are needed even if R&D efforts have paused?

No.

Future

What is planned for the next funding cycle and beyond? How, if at all, is this planning different from the original plan?

In response to the growing interest in LGAD technology for applications at the EIC, and to the concerns expressed by the committee, we have strengthened our team with additional members who have specific expertise on read out electronics.

M. Benoit (BNL) will contribute to the design and integration of off-detector readout based on Caribou/Felix boards, with focus on maximizing timing accuracy of the system, using TCAD and physics simulations as well as system testing.

The team from UCSC, A. Seiden, H. Sadrozinski and B. Schumm, have been leading the LGAD R&D effort for the HL-LHC, and have extensive expertise on electronics. In this project, they will contribute not only to the development and testing of the sensors, but also to the development of the architecture for the readout electronics. They will work in close collaboration with colleagues from Omega and IJCLab (FR), who have developed the ASIC readout chip for the ATLAS High Granularity Timing Detector (HGTD), known as ALTIROC [1,2], and have joined our team to study and develop a readout architecture for this project. The group from Omega and IJCLab includes R. Dupré, D. Marchand, C. Munoz Camacho, L. Serin C. de La Taille, M. Morenas.

The work planned for the next period is structured in three main tiers:

1. Studies of physics performance and detector specifications (Roman Pots and Preshower)
2. Detector R&D (slim-edge and pixelated AC-LGADs)
3. Design of a read-out architecture

The activities in 1) aim at advancing the studies leading to stringent specifications of the detector requirements in terms of time and space resolution, as well as the development of a strawman design of the detector layout.

The activities in 2) aim at concluding feasibility studies for AC-LADs in terms of ultimate time resolution, space resolution and slim-edges, by building small-scale prototypes leading to larger-scale prototypes that include all the features studied independently on small-area devices.

A priority for the activities to be conducted in the new period will be addressing one of the main concerns raised by the committee, i.e. the development of a readout strategy of such fast-time and pixelated AC-LGADs. This will be the focus of task 3) and for this we will collaborate with physicists, ASIC designers and engineers with prior experience on fast-time electronics for the HL-LHC.

Here follows a break-down of the plans in each of the above-listed tiers of research.

1) The detector simulation studies for the next R&D period will include the following
   a) beam+gas background studies and occupancies for the Roman Pot sensors, as well as studies on the Preshower. The background studies will be carried out using min-bias PYTHIA 6 and dpmJet simulations to simulate collisions of beam protons with gas molecules (mostly hydrogen) inside the beam pipe. These studies can give needed information on radiation requirements as well as background rates vs. true diffractive event rates.
   b) More detailed studies on the need for the edgeless sensor design, and the impact to low-p_T acceptance, since maximizing low-p_T acceptance of the scattered protons is of prime importance.
   c) A more realistic "strawman" sensor layout will be implemented to better understand the effect of real space and sensor shape constraints on the measurements.

2) The activities planned for the next period follow the successful results achieved with prototypes in the previous periods, and aim at building a larger scale prototype that includes all the features studied in independent small-scale prototypes.
   a) As soon as BNL infrastructures reopen we plan to finish the fabrication of zigzag strips that is close to completion, and was halted by COVID-19 closure of the lab, and immediately put them under test at BNL using laser and radioactive sources. Given the experience acquired with the previous test-beam at FNAL, in which we tested for the first time an AC-LGAD strip detector, and given the encouraging results, we plan to study these new zigzag AC-LGAD sensors in a test-beam at FNAL too.
   b) In parallel we are designing a double-metal technique for the definition of complex 2D metal patterns. Both the zigzag and double-metal patterns will exploit the potentials of novel centroid algorithms that will considerably improve the spatial resolution, in 1D and 2D respectively, beyond the strip pitch size of the detector.
   c) We plan to continue to investigate the trench termination as a slim edge option to reduce the inactive area and include it in a new fabrication of AC-LGADs with larger area and different electrode designs. The electrode shapes will be decided based on the experience acquired from the study of the AC-LGAD batches studied in a) and b).

3) A critical aspect for the development of a pixel or strip detector with fast-timing capabilities is the readout, since the front-end electronics must have timing and pitch size compatible with those of the sensor. Current ASICs for ATLAS (ALTIROC) and CMS (ETROC) are designed for the HL-LHC with pitch sizes of 1.3 x 1.3 mm^2, and are used together with LGAD sensors of the same pad size. These chips are designed in the CMOS TSMC 130 nm and CMOS 65 nm technologies respectively, and they use TDCs to measure the Time of Arrival and Time over Threshold, as well as RAM for data buffering. In the ALTIROC, for example, the maximum jitter is in the order of 25 ps for 10 fC charge, and the ALTIROC and ETROC total power consumption per unit area is about 200-300

mW / cm2. The ALTIROC and the ETROC chips host 225 and 256 channels respectively.

Within the time frame of this proposal we plan to study the requirements for the readout chain and start the design of the readout architecture. The co-investigators who have recently joined this project from BNL, UCSC and Omega / IJCLab will focus on the study of such readout architecture. Omega and IJCLab are leading the development of the ALTIROC chip. The anticipated experimental conditions at the EIC are quite different from HL-LHC, i.e. less radiation damage to sensor and electronics, therefore larger charge for a MIP, less stringent trigger/latency requirements etc.

a) We plan to study, starting from the ALTIROC chip, a possible architecture for the readout of Roman Pots using AC-LGADs and identify the missing ASIC blocks to be designed.
b) In parallel, using the existing ALTIROC1 prototype, we plan to study the time resolution performance of the Very Front End (preamplifier, discriminator + TDCs) with smaller granularity pads, specifically for the application in Roman Pots at EIC, assuming a pitch of 0.5x0.5 mm^2. The team from UCSC will collaborate closely with the OMEGA / IJCLab team to develop the readout strategy.

We are aware of the new proposal by F. Geurts (Rice), W. Li (Rice), S. Yang (Rice), C. Loizides (ORNL), C. Royon (Kansas), titled *"Precision Timing Silicon Detectors for Particle Identification and Tracking at EIC"*. Given the similarity of the two proposals, based on the same AC-LGAD sensor technology, we intend to closely collaborate with them and share expertise, resources, and results. We are also in close contact with other colleagues in the U.S.A with interests and experience in LGAD with the intent to build a U.S.-based consortium that exploits the capabilities of such a technology for EIC detectors.

What are critical issues?

The main single critical issue is the re-opening of the laboratories in BNL's Instrumentation Division and resume the fabrication and testing of the devices. In addition, two are the main critical issues related to the proposed project:

a) In so far as sensor R&D, the main critical issue is the convergence of the preliminary studies of different electrode shapes and slim edges such that we can start the production of a relatively large-scale prototype that includes those features and can be tested in the lab and in test-beams.
b) Develop a strategy that brings together accelerator experts, detector physicists and electronic engineers leading to the development of a readout strategy.

Additional information:

Manpower

A budget of $35,000 was requested for the 1st phase of the proposal, which included labor and M&S and is expected to be mostly spent by the end of FY20. Here follows more details how the original requested budget is being spent:

- $20,00 for sensor design and fabrication at BNL (0.10 FTE): Gabriele Giacomini, Wei Chen, and technicians (Instrumentation Division at BNL).
- $10,000 for silicon wafers and consumables for silicon fabrication
- The request included $5,000 for an international travel and subsistence for a student to visit BNL and join the local group on laboratory measurements for 2 months to test sensors. This will remain unused in FY20 due to COVID-19 travel restrictions.

The manpower for the new period is the same as the one committed in the previous period, with the additional effort from co-PIs who recently joined the team, and include contributed labor for simulations to determine scientific requirements, for the sensor development and testing, as well as for studies on electronics:

- 0.15 FTE E.C. Aschenauer to supervise the simulations to determine the scientific requirements.
- 0.4 FTE of Alex Jentsch a PostDoc in the group of E.C. Aschenauer to perform the needed simulations.
- 0.25 FTE of a PhD student (W. Chang) in the group of E.C. Aschenauer to perform the needed simulations
- 0.10 FTE of A. Tricoli in Physics Department to supervise a student, a professional and a PostDoc at BNL.
- 0.15 FTE of a BNL PostDoc and 0.10 FTE of a professional for laboratory measurements.
- 0.80 FTE of a BNL summer student.
- 0.10 FTE of C. Da Via at SBU/Manchester to supervise a student on sensor testing.
- 0.10 FTE of M. Benoit (BNL Physics Dept.) for electronic readout developments and simulations.
- 0.6 FTE, (50% engineers at OMEGA, 50% physicist at IJCLab involved in ATLAS and EIC studies) for ASIC design.
- 0.20 FTE from the UCSC team.

Funding Request for New Period

Costed Item	Direct Cost [$]
Labor for wafer fabrication	20,000
Materials for wafer fabrication (masks, implantation)	5,000
Travel	15,000
Total	**40,000**

Table 2: Break-down of budget request for Phase-2 of the project.

The request for funds in the new period follows closely the previous funding period, and it includes funds for labor for design and fabrication of silicon wafers in BNL’s Instrum. Div. ($20k), and materials for wafer fabrication at BNL ($5k). In addition, the budget includes 3 domestic travels for US-based collaborators, as well as 4 international travels for international co-PIs to visit BNL and participate in tests (total for travel $15k). The table below summarises the request for funds for a total of **$40k (direct).**

External Funding

For the simulation part of the proposal we utilize funds from the approved 3-year program development project "*eRHIC: from Virtual to Real*" of E.C. Aschenauer to support the labor needed to perform all the simulations. For the silicon R&D part of this project we will leverage resources from A. Tricoli's Early Career Award and LDRD for the development of fast-timing silicon detectors (LGADs) for HEP and photon science, respectively.

Submitted proposal: A.Tricoli as co-investigator in the project for the US-Japan Science Cooperation Program for HEP, titled *"Development of precision timing silicon detectors for future high energy collider experiments [renewal]"*, Request for $80,000 to BNL in FY20. Awaiting for official response from DOE.

Publications

1. A.Apresyan, G. Giacomini, A. Tricoli et al., "Measurements of an AC-LGAD strip sensor with a 120 GeV proton beam", sub. to JINST, https://arxiv.org/abs/2006.01999.

References

[1] Technical Design Report: A High-Granularity Timing Detector for the ATLAS Phase-II Upgrade. ATL-COM-UPGRADE-2020-01, to be published by September 2020 as CERN/LHCC document.

[2] C. Agapopoulou et al., Performance of a Front End prototype ASIC for picosecond precision time measurements with LGAD sensors, (2020), arXiv: 2002.06089 [physics.ins-det], accepted in JINST